METHOD, APPARATUS AND SYSTEM FOR PILOTLESS FREQUENCY OFFSET COMPENSATION IN MULTIPOINT-TO-POINT WIRELESS SYSTEMS WITH OFDM

This application is related to co-invented, co-owned U.S. Serial Nos. 10/342,519 filed Jan. 15, 2003, 10/406,776 filed April 3, 2003, 10/628,943 filed July 29, 2003, and 10/638,980 filed Aug. 12, 2003, all of which are hereby incorporated by reference herein in their entireties.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates broadly to telecommunications and data transmission via multiple telecommunication channels. The present invention more particularly relates to wireless telecommunication systems operating in radio channels with variable parameters. Specifically, the invention relates to multipoint-to-point (MPTP) wireless systems and networks with multicarrier orthogonal frequency division multiplexing (OFDM).

2. State of the Art

OFDM technology has well-known uses in a wide variety of wire and wireless telecommunication systems. The OFDM technique distributes and transmits data synchronously over a large number of carriers that are spaced apart at precise frequencies. OFDM is one of the most spectrally efficient transmission techniques. Among other advantages, multicarrier OFDM systems have a much lower symbol rate than equivalent single carrier systems.

In wireless channels, OFDM allows a system to mitigate the effects of multipath propagation and to provide a high data rate in the multipath environment. This technology is a basis for the Wireless Local Area Network (WLAN) IEEE.802.11a and IEEE.802.11g standards in the 5 GHz and 2.4 GHz frequency bands, respectively. According to the standards, the 52-carrier system provides up to 54 Mbit/s within a 20 MHz bandwidth in a multipath environment with path delays up to 800 nanoseconds (ns). OFDM technology is recommended in an IEEE 802.16 draft standard for fixed broadband wireless access systems in the frequency range 2-11 Ghz. The draft standard considers utilization of hundreds or even thousands of orthogonal carriers with QAM modulation. OFDM is also considered as a promising candidate for WLAN implementation in

the 60 GHz frequency band as well as for 3G mobile wireless systems.

Typical OFDM applications are point-to-point and point-to-multipoint (PTMP) transmissions. A point-to-multipoint application is illustrated in Fig. 1 where a central station (hub) and N user stations (nodes) are shown. The central station may be a base station (BS) in a mobile or fixed wireless network, or it may be an access point (AP) in a WLAN. The nodes may be any individual devices of the wireless network. For example, in the WLAN environment a node may be a PC, a laptop computer, a printer, a VoIP cordless phone, etc. Transmitted signals in the frequency domain are schematically shown at the bottom of Fig. 1 and consist of M carriers, numerated in the figure from 1 to M.

The key feature of the point-to-multipoint OFDM application is that the Hub sends a signal to all nodes simultaneously (in parallel), but only one of the nodes can transmit signal within the current time interval. Fig. 1 shows the example in which only the i-th node is currently transmitting a signal to the Hub, and only the i-th node is allowed to use carriers for data transmission at the given

moment. The active node can utilize the set of all carriers or any subset of carriers, but no other user can transmit any carrier at the same time. Practically this means that the system utilizes a type of time division access protocol, e.g., regular time division multiple access (TDMA) or random channel access based on carrier sense multiple access (CSMA). In other words, in PTMP applications, the nodes transmit their data within different, non-overlapping time intervals.

Point-to-multipoint OFDM transmission has the benefit of permitting the system to avoid the problems of differences in signal powers, frequency offsets and time delays for signals received from different nodes, because at any moment the receiver processes the signal from a single transmitter only. Therefore, the existing WLAN IEEE 802.11 standards support only point-to-multipoint transmission. Even with an ad hoc mode when there is no centralized controller-hub and one of the nodes provides the function of a temporary hub, the IEEE standard allows transmitting the signal only from one single transmitter at any moment.

On the other hand, the point-to-multipoint mode cannot efficiently exploit system capacity. For example, consider a

VoIP cordless phone as one of the nodes which does not need a high data rate but which requires a high quality digital voice transmission in real time. In this situation, when the cordless phone is active, it uses only a small part of the system capacity and forces all other nodes to wait for it to get off the air.

One possible way to increase the efficiency of OFDM utilization in a multi-user network is a multipoint-to-point (MPTP) mode that allows the nodes to transmit data simultaneously using a part of the system capacity for each node. This approach is considered for WLAN applications based on the IEEE 802.11a standard in McFarland, B. et al., "The 5-UP Protocol for Unified Multiservice Wireless Networks", IEEE Communications, Vol.39, No.11, November, 2001. A multipoint-to-point mode is illustrated in Fig. 2, which contains the same Hub and N nodes as in Fig.1.

The principal difference between multipoint-to-point OFDM and point-to-multipoint OFDM is that in multipoint-to-point OFDM all nodes have opportunity to send signal to the Hub simultaneously (in parallel) using the corresponding parts of a carrier set. As shown in the example of Fig. 2, the first

node (e.g., a cordless phone) transmits its data on the first carrier, the second node transmits on the second and (M-5)-th carrier, and so on. Distribution of carriers between the nodes is a function of the hub. Practically, this distribution, based on node demands, transforms the OFDM technique into the orthogonal frequency division multiple access (OFDMA) method.

In a real WLAN environment, OFDMA technology should be combined with some type of time division multiple access (TDMA). For example, if all carriers are currently distributed and used within a subset of nodes and some additional nodes demand communication, the system must assign some group of carriers for two or even more nodes, and these nodes will use the carriers in a time division mode.

OFDMA is an extended OFDM technique that provides the most efficient exploitation of the multicarrier system capacity. However, OFDMA has several additional issues as compared to the traditional point-to-multipoint OFDM. At the physical layer, all these issues are the result of differences in signal transformation and the propagation in paths from each individual node to the hub. As a result, groups of

carriers associated with different nodes have different powers, different frequency offsets, and different time delays. In addition, each carrier may have its own individual phase shift. The corresponding issues can thus be formulated as follows: 1) Power control for carrier groups; 2) Frequency offset compensation for carrier groups; 3) Individual carrier phase shift tracking; and 4) Time delay compensation for carrier groups.

A general approach to a solution of the above issues is described in McFarland, B. et al., "The 5-UP Protocol for Unified Multiservice Wireless Networks", IEEE Communications, Vol.39, No.11, November 2001. However, this paper does not contain any details allowing a real implementation of the system.

Methods and apparatus for power control in MPTP OFDM systems (issue #1 above) based on data carrier duplication were described in previously incorporated U.S. Serial No. 10/342,519 entitled "Method, Apparatus and System for OFDM Power Control". In addition, pilotless methods, apparatus and systems for frequency offset and phase shift tracking based on phase correction in the frequency domain (after FFT) in the

hub receiver (issue #2 above) were proposed in previously incorporated U.S. Serial No. 10/628,943 entitled "Pilotless, Wireless, Telecommunications Apparatus, Systems and Methods". However, neither of those disclosures provided a solution to frequency offset compensation for carrier groups in MPTP OFDM as the methods of frequency offset compensation disclosed in U.S. Serial No. 10/628,943 only partly solves the problem. The fact is that in the OFDM systems the frequency offset causes both carrier phase shifts and violation of carrier orthogonality. Violation of carrier orthogonality, in turn, causes considerable intercarrier interference. The disclosed algorithms in the previously incorporated patent applications provide phase shift compensation in frequency domain (after FFT), but they do not eliminate the intercarrier interference in the FFT.

On the other hand, if all carriers are utilized by one single node, then common frequency offset may be compensated in the hub receiver in the time domain, i.e. before FFT, to avoid the intercarrier interference. This approach is also disclosed in previously incorporated U.S. Serial No. 10/628,943 for point-to-multipoint applications. However, when different nodes use different groups (subsets) of

carriers simultaneously, and these groups have different frequency offsets, then compensation of frequency offset in the receiver in time domain is impossible.

One important aspect of frequency offset compensation in MPTP OFDM systems is that the problem is preferably solved on the basis of a "pilotless" approach; i.e., without the use of pilot carriers during data transmission. The pilotless approach allows a system to increase its real capacity. Moreover, while a point-to-multipoint system could in principle use fixed carriers as pilots, a MPTP pilot system needs at least one pilot carrier for each carrier group; and with respect to a flexible MPTP system, since the carrier group configuration may be changed from session to session, and the number of carriers within each groups is variable (from one carrier to the maximum possible carriers), the pilot approach is not a practical one for a flexible MPTP system implementation.

It should be appreciated that two types of pilot signals are usually used in wireless systems: preamble pilots which are transmitted during preamble before data transmission, and accompanying pilots which are transmitted during the whole

communication session in parallel with data transmission. In accord with the present invention, a pilotless approach permits use of the preamble pilots but does not utilize the accompanying pilots during data transmission at all.

In the context of the frequency offset problem, the preamble pilots provide rough compensation of the initial frequency offset. For example, if a typical frequency instability is equal to 20 ppm, then, in the frequency range 5 GHz, an up to 100 kHz frequency offset may be experienced. If the frequency interval between adjacent carriers is about 200-300 kHz, this offset cannot be compensated for during data transmission because the receiver is not capable to distinguish non-orthogonal carriers. So, for MPTP OFDM systems, the initial frequency offset should be compensated for in each transmitter within the initialization stage of the communication session (handshake). This initial compensation procedure, however, is outside the scope of the present invention. Nonetheless, even if frequency offsets are partially compensated during the handshake, the MPTP OFDM system must provide precise frequency offset compensation during the communication session in order to provide perfect

coherent signal processing. This precise frequency offset compensation is an important part of MPTP OFDM system design.

SUMMARY OF THE INVENTION

It is therefore object of the invention to provide multipoint-to-point, multicarrier, wireless, pilotless telecommunication systems, apparatus and methods which implement precise frequency offset compensation for carrier groups associated with different users.

It is an additional object of the invention to provide methods for the estimation of frequency offsets for carrier groups in the hub receivers of multipoint-to-point, multicarrier, wireless, pilotless telecommunication systems.

It is a further object of the invention to provide simply implementable algorithms and apparatus for estimation of frequency offsets for carrier groups in the hub receiver of a multipoint-to-point, multicarrier, wireless pilotless telecommunication system.

It is another object of the invention to provide methods for determining desired parameters of the frequency offsets for carrier groups, which should be transmitted from the hub to user nodes for the corresponding frequency offset correction in user transmitters.

An additional object of the invention is to provide algorithms and apparatus for frequency offset compensation in the user transmitters of multipoint-to-point, multicarrier, wireless, pilotless telecommunication systems.
A further object of the present invention is to provide multipoint-to-point, multicarrier, wireless, pilotless telecommunication systems, apparatus and methods which combine OFDMA and TDMA technologies to provide an efficient utilization of system capacity in a multiuser environment.

In accord with these objects, which will be discussed in detail below, the present invention provides methods, apparatus and systems for compensation of frequency offsets for carrier groups in the multipoint-to-point (MPTP), multicarrier OFDM, wireless, pilotless telecommunication systems. Broadly, the methods of the invention for implementing frequency offset compensation in the MPTP OFDM

systems includes: in the hub receiver, estimating frequency offset for each group of carriers in the frequency domain (after FFT); transmitting the frequency offset parameters for each group of carriers from the hub to the nodes; and in each node transmitter implementing frequency offset compensation in the time domain (after IFFT).

According to one aspect of the invention, algorithms of frequency offset estimation for groups of carriers are provided and are utilized by the hub receiver to support data transmission from nodes to the hub. The algorithms are based on reducing quadrature components or differential quadrature components of the received carriers and averaging the reduced components in two-dimensional space for K carriers within the group and for N symbols of each carrier. The reduction procedure involves all carriers utilized in the system and is not dependent on their combining in the groups. The averaging procedure on the other hand is carried out separately for each carrier group participating in the session.

According to another aspect of the invention, simplified algorithms of frequency offset estimation are provided for groups of carriers. The simplified algorithms are based on

utilization of a simple reference vector as well as on a majority vote algorithm which allows reduced components to be replaced with their signs. Replacement of the reduced components by their signs provides some mitigation of the effect of wrong decisions, because in this case any wrong decision cannot dramatically change the result. Additional robustness of simplified algorithms is achieved by using a lower bound for majority votes: if majority votes are less than some predetermined threshold, no corrections are provided.

Proposed estimates of frequency offsets are finally expressed preferably as sine and cosine functions of the phase shift caused by the frequency offset. These functions as well as any their transformations may be considered as the desired parameters of the frequency offset for the corresponding group of carriers. According to the invention, these parameters are transmitted from the hub to the node as a hub instruction for current frequency correction.

According to another aspect of the invention, the frequency offset compensation in the MPTP OFDM systems is provided in each node transmitter. In particular, during a

current telecommunication session with the hub, each node compensates its frequency offset as indicated by the hub by means of signal correction in the frequency and/or time domains. According to a preferred embodiment of the invention, frequency offset compensation is accomplished in the time domain based on linear transformation of complex samples of a signal at the output of the IFFT in the transmitter. Frequency offset compensation in the time domain after IFFT is the preferred method for digital implementation of the OFDM.

In accord with yet another aspect of the invention, the MPTP OFDM system of the invention is provided with an OFDMA/TDMA mode. In the MPTP OFDM system with combined OFDMA/TDMA mode, if the system capacity is sufficient to satisfy all current demands of the nodes in data transmission, then carriers are distributed within the nodes, and pure OFDMA mode is provided (using frequency offset compensation per carrier group according to other aspects of the invention). If the system capacity is not sufficient to satisfy all current demands of the nodes in data transmission, then a group of carriers is assigned to two or more nodes, and the

nodes utilize the group of carriers within non-overlapped time intervals according to any type of TDMA mode.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a high level schematic diagram of an OFDM point-to-multipoint mode telecommunication system of the prior art.

Figure 2 is a high level schematic diagram of an OFDM multipoint-to-point mode telecommunication system of the prior art.

Figure 3 is a high level schematic diagram of the proposed multipoint-to-point (MPTP) OFDM system with frequency offset compensation.

Figure 4 is a detailed schematic diagram of the Hub-site of the proposed MPTP OFDM system, including frequency offset estimation procedure for the carrier groups, based on differential quadrature components of the received carriers.

Figure 5 is a detailed schematic diagram of the Hub-site of the proposed MPTP OFDM system, providing simplified frequency offset estimation procedure for the carrier groups, based on the majority algorithm.

Figure 6 is a detailed schematic diagram of the User-site of the proposed MPTP OFDM system, providing frequency offset compensation in time domain for the carrier group in the node transmitter.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Turning now to Fig. 3, a high-level block diagram of a multipoint-to-point OFDM system 10 according to the invention is seen. The system 10 implements frequency offset compensation as will be described hereinafter. The system 10 is comprised of a hub 20 and a plurality of nodes (two shown) 40a, 40b. The hub includes a hub transmitter 22, a hub receiver 24, and a fast Fourier transform block 26 and an estimation block 28 which may be considered as part of the hub receiver. Each of the plurality of nodes 40a, 40b includes a node receiver 42a, 42b, a node transmitter 44a, 44b, and an inverse fast Fourier transform block 46a, 46b and a correction

block 48a, 48b which may be considered as part of the node transmitter.

In the MPTP OFDM system of the invention, each node (user) 40 has the opportunity to transmit data using a group of carriers (the "group" being as small as a single carrier and as large as all carriers), depending on its data rate demand and assignment from the hub 20. If all carriers were to be utilized by a single node, then a common frequency offset could be compensated for in the hub receiver in the time domain, i.e., before use of the FFT. In this case, the compensation algorithm is described as follows: Let S_m be the m-th complex sample of the received multicarrier symbol, frequency shifted by Δf Hz, where m is an integer changing from 1 to M, and M is the number of carriers in the multicarrier OFDM signal; then, the m-th sample of the compensated (frequency unshifted) signal S_{mc} is the complex number defined by

$$S_{mc} = S_m \exp(-jm\phi) \qquad (1.1)$$

where $\phi=2\pi\Delta fT$, and T is an FFT interval (interval of OFDM orthogonality).

However, when different nodes use different groups (subsets) of carriers simultaneously, and these groups have different frequency offsets, then compensation of frequency offset in the receiver in the time domain is impossible. In this case, and in accord with the invention, the compensation procedure is transferred to the transmitting nodes 40 which are correspondingly informed by the hub 20 regarding values of the frequency shifts within the carrier groups. In any individual node providing data transmission on a specified group of carriers, the samples at the output of the IFFT 46 of the node should be corrected by the correction block 48 as required by the hub 20.

Correction of the samples at the IFFT output in the transmitter can be provided according to equation (1.1), but in this case S_m will be the m-th complex sample of the transmitted signal at the output of IFFT, and S_{mc} will be the m-th sample of the compensated (frequency unshifted) signal in the transmitter. A detailed description of the corresponding algorithm is provided below with reference to Fig. 6.

So, according to the invention, a method of frequency offset compensation in MPTP OFDM systems includes steps of: in the hub 20, estimating the frequency offset in the frequency domain (i.e., after FFT) for each group of carriers; transmitting the frequency offset parameters for each group of carriers from the hub 20 to the nodes 40; and in each node, accomplishing frequency offset compensation in the time domain (i.e., after IFFT). This method is implemented in the system 10 of Fig. 3 with the frequency domain estimation of frequency offsets for all carrier groups accomplished in the estimation block 28 of the hub 20, and the frequency offset compensation (i.e., correction of complex samples of the carrier groups) accomplished in the correction blocks 48 of the nodes 40.

More particularly, during a telecommunication session between the hub 20 and the nodes 40, the hub 20 receiver 24 receives all transmitted carriers (as transmitted by the transmitters 44 of the nodes 40), and after their FFT transformation by FFT block 26, uses its estimation block 28 to provide a two-dimensional (in time and frequency domains) estimation of frequency offset parameters for all carrier groups (subsets of carriers) associated with different nodes participating in the session (as described in more detail

hereinafter with reference to Figs. 4 and 5). Then, the hub uses its transmitter 22 to transmit to all nodes 40 parameters of their frequency offsets as estimated. The nodes 40 receive the parameters via their receivers 42, and after inverse fast Fourier transform into the time domain via IFFT 46, each node compensates its frequency offset by means of the signal correction block 48 in the time domain.

It should be noted that during a current telecommunication session, each node 40 can also compensate its frequency offset in the frequency domain or in both frequency and time domains (as will be described hereinafter), but the correction blocks 48a, 48b of Fig. 3 shows only time domain correction after IFFT, which is the presently preferred embodiment of the invention from an implementation point of view.

As previously mentioned, according to the invention it is desirable to conduct a frequency offset estimation at the hub 20 for each carrier group utilized by different nodes 40 for data transmission to the hub 20. According to the preferred embodiment of the invention, the frequency offset estimation algorithms utilized are based on reducing and averaging

quadrature components or differential quadrature components of the received carriers. Two different frequency offset estimation algorithms are shown in flow-chart format in Figs. 4 and 5.

Before turning to Fig. 4, it is useful to provide the mathematical basis for the frequency offset estimation algorithms. In particular, if X_{kn} and Y_{kn} are quadrature components of the received n-th symbol of the k-th carrier, then the differential components of the n-th symbol of the k-th carrier dX_{kn} and dY_{kn} are calculated as follows:

$$dX_{kn} = (X_{kn} - X_{dkn}) \;, \qquad (2.1a)$$

$$dY_{kn} = (Y_{kn} - Y_{dkn}) \;, \qquad (2.1b)$$

where X_{dkn}, Y_{dkn} are quadrature components of a decision for the n-th symbol of the k-th carrier, which typically corresponds to a constellation point nearest to the received vector (X_{kn}, Y_{kn}).

Given the differential components of equations (2.1a) and (2.1b), the reduced differential components dX_{rkn} and dY_{rkn} of

the n-th symbol of the k-th carrier are determined according to

$$dX_{rkn} = (A_0/A_{kn})(dX_{kn}\cos\Delta_{kn} - dY_{kn}\sin\Delta_{kn}), \quad (2.2a)$$

$$dY_{rkn} = (A_0/A_{kn})(dY_{kn}\cos\Delta_{kn} + dX_{kn}\sin\Delta_{kn}), \quad (2.2b)$$

where Δ_{kn} is the phase difference between the decision vector for the n-th symbol of the k-th carrier and the reference vector, A_{kn} is the amplitude of the decision vector for the n-th symbol of the k-th carrier, and A_0 is the amplitude of the reference vector. It should be noted that, conceptually, any two-dimensional vector can be considered as the reference vector. In practice, however, some reference vectors may be more convenient than others. Two reference vectors in particular may have practical advantage: the first being a reference vector coinciding with one of the constellation points, and the second being a reference vector coinciding with X-axis or Y-axis in the two-dimensional space (e.g., vector (1,0) or (0,1)).

Just as the differential quadrature components of equations (2.1a) and (2.1b) can be reduced as in equations (2.2a) and (2.2b), quadrature components of the received

carriers X_{kn} and Y_{kn} may also be directly reduced to the corresponding components X_{rkn} and Y_{rkn} of the reference vector:

$$X_{rkn} = (A_0/A_{kn})(X_{kn}\cos\Delta_{kn} - Y_{kn}\sin\Delta_{kn}), \qquad (2.2c)$$

$$Y_{rkn} = (A_0/A_{kn})(Y_{kn}\cos\Delta_{kn} + X_{kn}\sin\Delta_{kn}) . \qquad (2.2d)$$

The reduced differential components dX_{rkn} and dY_{rkn} as well as reduced quadrature components X_{rkn} and Y_{rkn} may be averaged both in the time domain and in the frequency domain, i.e., through indexes n and k, correspondingly. If the considered group of carriers has a common frequency shift, then a result of averaging in time and frequency domains will be to detect this common frequency shift.

A general expression for the two-dimensional averaging of reduced differential components dX_{rkn} and dY_{rkn} within a group of K carriers on N symbol intervals for each carrier can be presented as follows:

$$dX_r = (1/KN)\sum dX_{rkn} = (A_0/KN)\sum_{k=1}^{K}\sum_{n=1}^{N}(dX_{kn}\cos\Delta_{kn} - dY_{kn}\sin\Delta_{kn})/A_k \qquad (2.3a)$$

$$dY_r = (1/KN)\sum dY_{rkn} = (A_0/KN)\sum_{k=1}^{K}\sum_{n=1}^{N}(dY_{kn}\cos\Delta_{kn} + dX_{kn}\sin\Delta_{kn})/A_{kn} \qquad (2.3b)$$

Likewise, the reduced quadrature components of the received carriers X_{rkn} and Y_{rkn} from (2.2c) and (2.2d) may be averaged according to:

$$X_r = (1/KN)\sum X_{rkn} = (A_0/KN) \sum_{k=1}^{K}\sum_{n=1}^{N} (X_{kn}\cos\Delta_{kn} - Y_{kn}\sin\Delta_{kn})/A_{kn}, \quad (2.3c)$$

$$Y_r = (1/KN)\sum Y_{rkn} = (A_0/KN) \sum_{k=1}^{K}\sum_{n=1}^{N} (Y_{kn}\cos\Delta_{kn} + X_{kn}\sin\Delta_{kn})/A_{kn}, \quad (2.3d)$$

As will be appreciated by those skilled in the art, the averaging procedure of equations (2.3) involves components of K carriers and N symbols for each carrier. The values utilized for K and N preferably depend on the required number of averaged components necessary and sufficient for reliable estimates. For example, if R is the desired number of averaged components for a reliable estimate, then

$R=KN.$

(2.4)

Simulations of OFDM systems in typical WLAN conditions show that $R\approx50$ is generally sufficient for a precise

estimation of frequency offset. Thus, according to one preferred aspect of the invention,

$$KN \approx 50 \ . \tag{2.5}$$

Those skilled in the art will appreciate that the number N of averaged symbols thus depends on the size K of the carrier group. A first extreme case is where the carrier group contains sufficient numbers of carriers such that N can equal 1. In this case averaging can be completely provided in the frequency domain. A second extreme case is where a group contains a single carrier (i.e., K=1). In this case, averaging is completely provided in the time domain.

The estimates X_r and Y_r from equations (2.3c) and (2.3d) are approximate coordinates of a new reference vector, shifted relative to the initial one because of frequency offset, and the estimates dX_r and dY_r from (2.3a) and (2.3b) are approximate coordinates of the difference between the shifted reference vector and the reference vector. These estimates (X_r and Y_r or dX_r and dY_r) permit the expression of a phase shift caused by the frequency offset as a phase angle ϕ.

Taking into account that the shifted reference vector has coordinates X_0+dX_r and Y_0+dY_r, where X_0 and Y_0 are coordinates of the reference vector, trigonometric functions of the phase ϕ can be derived as follows:

$\mathrm{Sin}\phi = [(X_0+dX_r)Y_0 - (Y_0+dY_r)X_0]/A = [dX_rY_0 - dY_rX_0]/A,$ (2.6a)

$\mathrm{Cos}\phi = [(X_0+dX_r)X_0 + (Y_0+dY_r)Y_0]/A = [(A_0)^2 + dX_rX_0 + dY_rY_0]/A,$ (2.6b)

where $A = A_0*[(X_0+dX_r)^2 + (Y_0+dY_r)^2]^{0.5}$. If, for example, the reference vector has coordinates $X_0=1$ and $Y_0=0$, then equations (2.6a) and (2.6b) reduce as follows:

$$\mathrm{Sin}\phi = -dY_r/A \qquad (2.6c)$$

$$\mathrm{Cos}\phi = (1+dX_r)/A \qquad (2.6d)$$

If the amplitude change of the reference vector (due to noise) is negligible, then equations (2.6c and (2.6d) further reduce according to

$$\mathrm{Sin}\phi \approx -dY_r, \qquad (2.6e)$$

$$\mathrm{Cos}\phi \approx 1. \qquad (2.6f)$$

As will be appreciated by those skilled in the art, the trigonometric functions of phase ϕ can also be derived through estimates X_r and Y_r from equations (2.3c) and (2.3d) as follows:

$$\mathrm{Sin}\phi = (X_r Y_0 - Y_r X_0)/A, \qquad (2.7a)$$

$$\mathrm{Cos}\phi = (X_r X_0 + Y_r Y_0)/A, \qquad (2.7b)$$

where $A = A_0[(X_r)^2 + (Y_r)^2]^{0.5}$. If, for example, the reference vector has coordinates $X_0=1$ and $Y_0=0$, then equations (2.7a) and (2.7b) reduce as follows:

$$\mathrm{Sin}\phi = -Y_r/A, \qquad (2.7c)$$

$$\mathrm{Cos}\phi = X_r/A. \qquad (2.7d)$$

If the amplitude change of the reference vector (due to noise) is negligible, then equations (2.7c) and (2.7d) further reduce to

$$\mathrm{Sin}\phi \approx -Y_r, \qquad (2.7e)$$

$$\mathrm{Cos}\phi \approx 1. \qquad (2.7f)$$

Estimates (2.6) and (2.7), which are the sine and cosine functions of the phase shift caused by the frequency offset, may be considered as the desired parameters of the frequency offset for the corresponding group of carriers. According to the invention, these parameters are transmitted from the hub 20 to the node 40 utilizing the corresponding group of carriers.

It should be appreciated that any other transformations of estimates (2.6) and (2.7) can be also used as the parameters of the frequency offset and be transmitted from the hub to the nodes. For example, functions $\mathrm{Sin}\phi$ and $\mathrm{Cos}\phi$ can be combined into one single number for transmission to the corresponding node:

$$\phi = \mathrm{arctg}(\mathrm{Sin}\phi/\mathrm{Cos}\phi). \qquad (2.8)$$

In turn, the phase parameter of equation (2.8) can be transformed into a frequency parameter and expressed in Hz:

$$\Delta f = \phi/2\pi T \qquad (2.9)$$

Given the above, according to the invention, a preferred general algorithm for frequency offset estimation comprises (the algorithm being described in parallel for both differential quadrature components and quadrature components of the received signal):

1) After FFT in the hub receiver, a set of quadrature components X_{kn} and Y_{kn} of the received carriers at the n-th symbol interval is used for making multicarrier current decisions X_{dkn} and Y_{dkn} , and differential quadrature components of the carriers dX_{kn} and dY_{kn} are calculated according to equation (2.1);

2) Using the current decisions, the set of differential quadrature components dX_{kn}, dY_{kn} or the set of quadrature components X_{kn}, Y_{kn} is reduced according to equation (2.2) for all carriers;

3) Reduced differential quadrature components dX_{rkn}, dY_{rkn} or reduced quadrature components X_{rkn},Y_{rkn} are averaged within each group of carriers associated with different users in the frequency domain (K carriers of a group) and in the time domain (N symbols of each carrier) to find estimates of a differential reference vector dX_r ,dY_r or a reference vector X_r, Y_r for each carrier group according to equation (2.3);

4) Using estimates of the differential reference vector dX_r, dY_r or reference vector X_r, Y_r, trigonometric functions of phase shifts for each carrier group are calculated according to equations (2.6) or (2.7); and

5) Upgraded parameters of frequency offsets for carrier groups according to equations (2.6), (2.7), (2.8), or (2.9) or their transformations, are transmitted by the hub transmitter to all nodes participating in the session.

The general algorithm for frequency offset estimation based on differential quadrature components of the received carriers is illustrated in Fig. 4, which shows a block and flow diagram of the hub 20 of the MPTP OFDM system 10. In Fig. 4, bold lined blocks carry out the frequency offset estimation algorithm, while the remaining blocks are a conventional part of the receiver. It should be noted that the FFT unit 26, the multicarrier decision unit 102, the differential components calculator 104, and the soft decoder 106 are shown apart from the hub receiver 24 so that their connections to the estimating procedure can be more easily seen, as their signals are partly used in the algorithm.

The conventional part of the hub receiver operates as follows. Digital samples of the n-th received multicarrier symbol are fed to the FFT unit 26. Complex numbers (X_{kn}, Y_{kn}) for the whole set of carriers from the output of the FFT are fed to multicarrier decision unit 102 where current decisions (X_{dkn}, Y_{dkn}) for all carriers are made. Decisions (X_{dkn}, Y_{dkn}) are typically used for the calculation of differential quadrature components (dX_{kn}, dY_{kn}) of the received carriers by calculator 104 according to equation (2.1), which, in turn, are used in the soft decoder 106. Corrected symbols from the soft decoder are then fed to output circuits (not shown) of the hub receiver 24.

According to the invention, the differential quadrature components (dX_{kn}, dY_{kn}) calculated by differential components calculator 104 are reduced at 111 according to equations (2.2a) and (2.2b). The reduction procedure also utilizes parameters of signal reduction Δ_{kn}, A_0, A_{kn} or their combinations such as A_0/A_{kn} stored in the parameters memory 113. Additionally, the reduction procedure can utilize exclusion of unreliable symbols from the further processing as described in previously incorporated U.S. Serial No. 10/628,943. The exclusion signal (if applied) is provided by

the unreliable symbols exclusion block 115 located between the soft decoder 106 and the reduction unit 111. The unreliable symbols exclusion block 115 utilizes information regarding symbol reliability from the soft decoder 106.

It should be noted that the reduction procedure 111 involves all carriers utilized in the system and does not depend on their combination in carrier groups. In contrast to the reduction procedure, the averaging procedure 117 is carried out separately for each carrier group participating in the session, according to equations (2.3a) and (2.3b). For each carrier group averaging can involve different numbers of carriers K and different numbers of symbols N. The averaging unit 117 provides estimates dX_r and dY_r (i.e., approximate coordinates of the difference between the shifted reference vector and the reference vector) for each carrier group. These estimates are then utilized by the phase shift estimation block 119 to generate functions of the phase ϕ according to equations (2.6) for each carrier group (e.g., $\sin\phi$ and $\cos\phi$). These functions may then be modified in block 121 as in equations (2.8) or (2.9) to provide indications of the phase shift for each carrier group which are fed to the

hub transmitter 22 to be transmitted to the nodes 40 as a hub instruction for current frequency correction.

As previously suggested, the general algorithm for frequency offset estimation as described with reference to Fig. 4 can be simplified. The simplification of frequency offset estimation algorithm for carrier groups is based on the fact that, if the reference vector is chosen carefully, the trigonometric functions of phase reduce and can be represented in other manners. For example, if the reference vector is chosen to be (1,0), then a sign of the Y-coordinates of the **reduced differential vectors or corrected reference vectors** coincides with a sign of the received vectors phase shift, and the phase shift is proportional to the absolute value of the Y-coordinates of the vectors. So, using equations (2.6e) and (2.7e),

$$\mathrm{Sin}\phi \approx -dY_r = (A_0/KN) \sum_{k=1}^{K}\sum_{n=1}^{N} (dY_{kn}\cos\Delta_{kn} + dX_{kn}\sin\Delta_{kn})/A_{kn}. \quad (2.10a)$$

$$\mathrm{Sin}\phi \approx -Y_r = (A_0/KN) \sum_{k=1}^{K}\sum_{n=1}^{N} (Y_{kn}\cos\Delta_{kn} + X_{kn}\sin\Delta_{kn})/A_{kn}, \quad (2.10b)$$

$\mathrm{Sin}\phi$ values may then be directly utilized as desired parameters of frequency offset or they can be used as the

basis for transformed parameters such as the transformed parameters set forth in equations (2.8) and (2.9).

Further simplification of frequency offsets estimation for carrier groups is based on majority vote approach where the accumulation of terms in equations (2.10a) or (2.10b) is replaced by an accumulation of their signs. The procedure includes two steps: simplified reduction of the received vectors for all carriers, and accumulation of signs of the reduced components for carrier groups.

The simplified reduction procedure includes only the Y-coordinate of the reduced vector and only one decision parameter Δ_{kn}:

$$dY_{rkn} = (dY_{kn}\cos\Delta_{kn} + dX_{kn}\sin\Delta_{kn}) , \qquad (2.11a)$$

$$Y_{rkn} = (Y_{kn}\cos\Delta_{kn} + X_{kn}\sin\Delta_{kn}) . \qquad (2.11b)$$

Signs of the reduced components (2.11a) or (2.11b) are then accumulated (majority votes) for each carrier group according to

$$D_{+-} = \sum_{k=1}^{K}\sum_{n=1}^{N} \text{Sign}\ (dY_{kn}\cos\Delta_{kn} + dX_{kn}\sin\Delta_{kn}), \qquad (2.12a)$$

$$D_{+-} = \sum_{k=1}^{K}\sum_{n=1}^{N} \text{Sign}\ (Y_{kn}\cos\Delta_{kn} + X_{kn}\sin\Delta_{kn}), \qquad (2.12b)$$

where Sign(x) = +1 or -1. The resulting integer D_{+-} is the difference between the number of components with positive phase shifts and a number of components with negative phase shifts. This integer reflects carrier majority vote, and its sign determines a direction for frequency offset adjustment.

The integer value obtained pursuant to equations (2.12a) and (2.12b) can serve as a parameter of frequency offset for the corresponding carrier group. In this case, the value should be transmitted to the node transmitter and utilized for offset compensation.

It should be noted that replacement of terms in equations (2.10) by their signs in equations (2.12) provides some mitigation of the effect of wrong decisions, because with the use of signs, wrong decisions cannot dramatically change the result. Additional robustness of equations (2.12) may be achieved by using a lower bound for majority votes. For example, if the modulo of D_{+-} is less than some predetermined

threshold T_d, no corrections are provided. The threshold T_d may be chosen to depend on the number of components in equations (2.12), which is preferably equal to KN. According to a preferred aspect of the invention, a threshold equal to approximately 10% of all components participating in averaging is utilized and is believed to provide a desired robustness to the system.

Since integer D_{+-} from equations (2.12) determines only a direction of frequency offset adjustment, it is desirable also to obtain a value (size) of the adjustment. Different mechanisms for obtaining frequency offset compensation value are available. A first mechanism involves averaging projections of the component majority. In this mechanism, differential carrier projections or carrier projections are accumulated as in equations (2.10) only for components from the majority votes, and then the resulting value is divided by the number of majority components. For example, if the total number of components is equal to KN, then the number of majority components is equal to $(KN + |D_{+-}|)/2$. In other words, in this mechanism the frequency offset is corrected by the projections corresponding to the largest number of occasions.

It should be noted that the method has shown good results in the system simulation.

Another mechanism of determining the frequency offset value is based on an assumption that the frequency is slowly changing and can be efficiently corrected by changing the carrier frequency with a constant small increment. In this case the frequency offset estimation algorithm should determine only a direction of the adjustment. In turn, the adjustment direction Sign(ϕ) can be found as a sign of value D_{+-} from (2.12):

$$\mathrm{Sign}(\phi) = \mathrm{Sign}\left[\sum_{k=1}^{K}\sum_{n=1}^{N} \mathrm{Sign}\left(dY_{kn}\cos\Delta_{kn} + dX_{kn}\sin\Delta_{kn}\right)\right], \quad (2.13a)$$

$$\mathrm{Sign}(\phi) = \mathrm{Sign}\left[\sum_{k=1}^{K}\sum_{n=1}^{N} \mathrm{Sign}\left(Y_{kn}\cos\Delta_{kn} + X_{kn}\sin\Delta_{kn}\right)\right], \quad (2.13b)$$

It should be noted that the mechanism of changing the carrier frequency with a constant small increment is the simpler of the two mechanisms because it does not require a calculation of the frequency shift value. Its disadvantage, on the other hand, is that it cannot provide the precise proper constant increment for a wide range of frequency offset.

Based on the above, the simplified algorithm of frequency offset estimation can be described as follows (the algorithm is described in parallel for both differential quadrature components and quadrature components of the received signal):

1) After a FFT in the hub receiver, a set of quadrature components X_{kn} and Y_{kn} of the received carriers at the n-th symbol interval is used for making multicarrier current decisions X_{dkn} and Y_{dkn}, and differential quadrature components of the carriers dX_{kn} and dY_{kn} are calculated according to equations (2.1);

2) Using the decisions, the set of differential quadrature components dX_{kn}, dY_{kn} or the set of quadrature components X_{kn}, Y_{kn} is reduced according to equations (2.11) for all carriers;

3) Signs of the reduced differential quadrature components dY_{rkn} or reduced quadrature components Y_{rkn} are accumulated within each group of carriers associated with different users, in the frequency domain (K carriers of a group) and in time domain (N symbols of each carrier), and then transformed into an integer D_{+-} according to majority vote algorithm according to equations (2.12);

4) If D_{+-} is more than some predetermined threshold T_d, the direction of frequency correction is determined by the sign of

D_{+-} according to equations (2.13), and the frequency offset value is determined to equal either the average offset of the majority components or a predetermined constant increment;

5) The upgraded parameters of frequency offsets for the carrier groups (i.e., the sign of the frequency adjustment and the frequency offset values for the carrier groups) are transmitted by the hub transmitter to all nodes participating in the session.

The simplified algorithm of frequency offset estimation is illustrated in the block and flow diagram of Fig. 5. As in Fig. 4, the bold lined blocks of Fig. 5 carry out the frequency offset estimation algorithm of the invention in the receiver of the hub 20, while the remaining units (the FFT 26, the multicarrier current decision unit 102, the differential components calculator 104, and the soft decoder 106) are part of a conventional hub receiver. Operation of this conventional part of the receiver was described above with reference to Fig. 4.

Operation of the frequency offset estimate blocks of Fig. 5 is as follows. Differential quadrature components (dX_{kn}, dY_{kn}) determined by block 104 are subjected to simplified

reduction at 131 according to equations (2.11). The reduction procedure 131 utilizes parameters of signal reduction Δ_{kn} stored in the parameters memory 114. It should be noted that the reduction procedure involves all of the carriers utilized in the system and is not dependent on their combination in groups. In contrast to the reduction procedure, the vote procedure at 133 according to equations (2.12) is carried out separately for each carrier group participating in the session. Calculation of a final sign at 135 according to equations (2.13) for each group can involve different numbers of carriers K and different numbers of symbols N. Finally, upgraded parameters of frequency offset are fed to the hub transmitter 22 to be transmitted to the nodes 40 as a hub instruction for current frequency correction.

As previously suggested, according to the invention, the frequency offset compensation information (i.e., the parameters) for the MPTP OFDM system is provided by the hub 20 to each node 40. Thus, during a current telecommunication session with the hub, each node compensates its frequency offset as indicated by the hub by means of a signal correction in the frequency and/or time domain.

There are different approaches to frequency correction in a radio transmitter. A traditional approach consists in the proper change of local oscillator frequency by Δf Hz determined via equation (2.9). In digital implementations of the OFDM algorithm, the preferable method for frequency correction is frequency offset compensation in the time domain after IFFT. This method can be described as follows. Let X_m and Y_m be the real and imaginary parts of the m-th complex sample of a signal at the output of the IFFT in the node transmitter, where m is an integer changing from 1 to M, and M is the number of carriers in the multicarrier OFDM signal. Also assume that the signal is frequency shifted by Δf Hz. Then, taking into account equation (1.1), the real and imaginary parts X_{mc} and Y_{mc} of the m-th corrected sample are equal to

$$X_{mc} = X_m \cos(m\phi) + Y_m \sin(m\phi)\,, \qquad (3.1a)$$

$$Y_{mc} = Y_m \cos(m\phi) - X_m \sin(m\phi)\,, \qquad (3.1b)$$

where $\phi = 2\pi\Delta f T$, and T is an FFT interval.

It should be noted that in real computation algorithms, the product $m\phi$ in brackets of equations (3.1) is calculated

modulo 2π. Further computation of $\cos(m\phi)$ and $\sin(m\phi)$ is typically provided by means of the stored table of sine and cosine functions within a 2π interval.

Implementation of equations (3.1) is illustrated in Fig. 6, which shows a detailed schematic diagram of the user-site (node) 40 of the MPTP OFDM system 10 of the invention, including the frequency offset compensation procedure in the time domain for the carrier group utilized by the node. In the block-diagram of Fig. 6, the bold lined units carry out the frequency offset compensation algorithm of the invention. The remaining units such as the IFFT 162 and the modulator 164 are conventional parts of the OFDM transmitter which are shown separately from the node transmitter 42 so that their connections to the compensation algorithm is more evident.

The frequency offset compensation algorithm is implemented using a phase multiplier "$m\phi$" 170, a table of Sine and Cosine functions 172, and a correction of complex samples block 174. During the session with the hub 20, the node 40 receives a frequency-offset parameter for its carrier group. In Fig. 6 the parameter is shown as a phase shift $\phi = 2\pi\Delta fT$. This phase shift is modulo 2π multiplied at 170 by numbers

$m=1,2, \ldots, M$, where M is a total number of carriers in the system and m increases synchronously with the corresponding samples at the output of the IFFT 162. The multiplied phase $m\phi$ is fed to a Sine and Cosine functions table 172 which provides sine and cosine values to the correction block 174. Correction block 174 corrects the complex samples (X_m, Y_m) generated by the IFFT according to equations (3.1). The corrected complex samples (X_{mc}, Y_{mc}) are fed to the transmitter modulator 164. With the provided corrections, the modulator 164 may then properly modulate all input data signals to be transmitted by the node transmitter 44 to the hub.

It should be noted that during a current telecommunication session with the hub 20, each node 40 can compensate its frequency offset in the frequency domain or in the time domain or in both the frequency and time domains. According to a preferred aspect of the invention, the initial frequency offset is roughly compensated in the frequency domain, while precise frequency offset tracking is provided in the time domain. More specifically, during a handshake between a hub and a node the hub receives a pilot signal from the node and roughly measures the frequency offset of this particular node transmitter. In the handshake period of time

(before data transmission) the hub can assign a special set of carriers (group of carriers) for the node or the group of carriers may be predetermined for the node. In any case, during the handshake or preamble the hub transmits a frequency offset parameter to the node, and the node compensates using the indicated frequency shift in the frequency domain, for example, by changing the reference oscillator frequency. This provides a rough compensation of frequency offset. Then, during data transmission (the session), the precise compensation of the frequency offset is provided based on the previously described methods of the invention; i.e., the hub estimates the frequency offset for the carrier group, transmits frequency offset indications to the node, and the node compensates for the offset in the time domain.

According to another aspect of the invention, all of the previously described procedures for frequency offset compensation may be utilized in either a pure OFDMA mode or in a combined OFDMA/TDMA mode. In the pure (typical) OFDMA mode, the hub distributes all carriers or a subset of carriers among the nodes currently participating in a communication session, and all groups of carriers associated with different nodes are subjected to frequency offset compensation according to the

proposed algorithms. In the combined OFDMA/TDMA mode, some group of carriers or part of a group (e.g., even a single carrier) can be assigned for utilization in two or more nodes. In this case, the nodes utilize the same carrier(s) within different time intervals according to a regular TDMA schedule indicated by the hub, or according to random channel access based, for example, on carrier sense multiple access (CSMA). In the combined OFDMA/TDMA mode, the frequency offset compensation procedure differs from the frequency offset compensation procedure of the pure OFDMA mode in substantially one only aspect: a subset of carriers utilized by two or more nodes is subjected to frequency offset compensation separately for each node associated with that subset of carriers. As a result, the hub must estimate frequency offsets not only for each group of carriers but also for each node utilizing the same group of carriers.

It will be appreciated by those skilled in the art that the flow charts of Figures 3-6 may be implemented in hardware, software, firmware, dedicated circuitry or programmable logic, digital signal processors, ASICS, or any combination of them.

There have been described and illustrated herein several embodiments of methods, systems and apparatus for pilotless frequency offset compensation in multipoint-to-point wireless systems with OFDM. While particular embodiments of the invention have been described, it is not intended that the invention be limited thereto, as it is intended that the invention be as broad in scope as the art will allow and that the specification be read likewise. Thus, while particular reference vectors have been disclosed as preferred, it will be appreciated that other reference vectors could be utilized as well. In addition, while particular frequency offset parameters were described as preferred for transfer from the hub to the nodes, it will be understood that other parameters (i.e., indications of frequency offset) could be provided. Also, while embodiments of the invention have been shown in the drawings in flow-chart format with particular function blocks, it will be recognized that the functionality of various of the blocks could be split or combined without affecting the overall approach of the invention. Further, while the invention was disclosed with reference to a soft decoder, it will be appreciated that a hard decoder could be utilized alone or in conjunction with the soft decoder, and that one or the other will suffice. It will therefore be

appreciated by those skilled in the art that yet other modifications could be made to the provided invention without deviating from its spirit and scope as claimed.